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MATERIALS AND STRUCTURES FOR MANNED SPACE STATIONS

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One of the more important problem areas in the development of manned orbiting space stations concerns materials and structures. In this area the living quarters which would house the crew have been of prime interest since they appeared to require the most research effort. As has been indicated in a preceding article, the living quarters might be constructed of rigid modules, a combination of rigid and inflatable sections, or of inflatable sections made entirely of flexible materials. Since it was obvious that the state-of-the-art concerning flexible materials and inflatable structures was many years behind that of rigid materials and structures, it was decided that a concentrated effort was needed on inflatables in order to catch up. Therefore, most of the research to date has been in this area.

The living quarters cabin of a manned orbiting space station must have a unique and quite exacting set of properties. In general, the structure and materials used in it must be strong and light, must be able to withstand the space environment, must be nonhazardous to man, and, in the case of an inflatable cabin, must be flexible and packageable. Specific properties and requirements are listed in the accompanying table. Of the loads mentioned, the largest one on the cabin wall will probably be imposed by internal pressure. The walls will be required to operate in a hard vacuum; the pressure at an altitude of 300 nautical miles is only of the order of 10^{-8} mm Hg. The particle radiation hazard is not considered a major problem since exposure can be minimized by keeping the orbit of the station beneath the Van Allen belts.

Now, it is apparent upon considering these requirements that no one material can be used to construct the wall of the living quarters of a space station.

A typical wall section will therefore probably be of the multilayer or composite type whether the wall be rigid or flexible. Going from the inside to the outside of the wall there might be a coating for interior color and abrasion resistance, a coating for control of gas permeability, elements designed to take the structural loads, a layer of insulation, a micrometeoroid bumper, and, on the outside, coatings for temperature control.

Our configuration studies have indicated that the cabin might be toroidal shaped, and therefore several ways of constructing the load-carrying portion of inflatable toroids have been investigated. One of these employs a filament cage and bladder, and a torus model having an overall diameter of 24 feet and a cross-sectional diameter of 8 feet has been built using this principle. The cage is designed to take the major pressure loads and is constructed of 80-mil dacron cords or filaments, arranged meridionally around the torus. At the inner rim of the torus, the cords are wound around a 1-inch-diameter cable which is clamped to an 8-ft. -diameter rigid central hub. A 8-mil-thick bladder made of butyl impregnated nylon placed inside the cage contains the inflation gases and carries the relatively small local longitudinal loads. After initial inflation to shape during fabrication, the cords are combed parallel and stuck down to the bladder with polyurethane cement. This torus has an operating pressure of 7 psi, which corresponds to a wall stress of about 360 pounds per linear inch, and it has a design burst pressure of 35 psi, giving a safety factor of five. It weighs 280 pounds, and has a volume of about 2200 cubic feet when inflated.

The composite material has a strength of over 1800 pounds per linear inch and weighs only about 0.25 pounds per square foot. This material is foldable, and tests have indicated that the torus can be packaged around the hub so that

it occupies a volume equal to only 2 percent of its inflated volume. Repeated folding and inflation tests have indicated no structural damage due to the packaging. In addition to structural integrity, shape stability, and packaging and deployment tests, the 24-foot model is being used to investigate arrangement of internal furnishings and controls, air circulation and leak rates. A second test phase will include deployment and leak-rate studies in a large vacuum chamber under simulated space environment conditions.

A second method of structural skin construction employs an isotensoid concept. This is a filament winding process wherein the winding geometry and the cross-sectional shape of the structure are matched so that all primary loads are carried by filaments or cords having equal tension, and no load is carried by the flexible binder or elastomer. We have recently investigated a 45-inch-outside-diameter torus constructed using this technique. This model had 10-inch-diameter cross sections and contained no central hub. It was constructed of multiple meridional windings and inner and outer equatorial reinforcing bands to take the overall longitudinal loads and to provide shape stability. The model was 1/8 scale, but was designed for a pressure of 8 times the operating pressure of 7 psi (56 psi) so that the design skin would have full-scale thickness and stresses. Design burst pressure was 280 psi. The materials used were 12-mil dacron cords and a polyurethane elastomer.

The resulting composite material had a tensile strength of over 1800 pounds per linear inch, or 56,000 psi based on the thickness of the material which was only about 32 mils. It weighed approximately 0.25 pounds per square foot. It was not readily foldable, however, probably because of the small amount of elastomer contained in the composite — only about 20 percent. Pressure tests indicated a failure of the structure at approximately twice

the design operating pressure or 40 percent of design burst pressure. The failure was not due to a breaking of the cords but occurred because of localized spreading apart of adjacent cords where they had no support perpendicular to their length except for the low-strength elastomer. This result was not unexpected since the inner and outer equatorial bands do not provide resistance to local longitudinal loads. These deficiencies have been corrected in the design of a second 45-inch-diameter torus. Double helix windings are utilized so that local longitudinal strength is provided anywhere on the torus, and foldability is improved by modifying the elastomer content.

A third way of constructing the structural skin employs the pattern layup method, wherein gores of a special 3-ply fabric are joined together to form the torus. Each ply is constructed of a flexible elastomer and flexible cord reinforcements with all the filaments in a given ply being parallel to one another. The plies are arranged so that the cords of one are oriented meridionally on the torus, and the cords of the other two plies are oriented approximately 45° to either side of the meridional ply. This allows the fabric to handle the approximately 2-to-1 stress ratio in the torus skin.

Samples of such composite materials have been constructed of a butyl rubber elastomer and dacron cords. One of these fabrics is 1/10 of an inch thick and weighs about 0.6 pounds per square foot. It has a maximum tensile strength of 1800 pounds per inch, or 18,000 psi based on the 1/10-inch thickness. It is easily foldable, containing approximately 65 percent elastomer. Another fabric of comparable strength per inch has also been developed; it contains about 45 percent elastomer, is 0.07 inches thick, and weighs about 0.42 pounds per square foot. While its folding characteristics appear to be satisfactory,

it is not as easy to fold as the 1/10-inch fabric. One disadvantage of this type of construction is that the gores must be put together in some manner so that the full strength of the basic material may be realized. But, as is well known, some elastomers such as butyl are hard to bond. We are presently working on this problem, howver, and are hopeful of achieving satisfactory results.

The approach to construction of rigid walls is relatively conventional, has been discussed in a preceding article, and therefore will not be further described here.

Many of the materials available for use in constructing a manned space station have been tested by the manufacturer, and the results are available in current publications. The properties evaluated in these tests, however, are usually those of concern at the surface of the earth. Little information is available on properties such as effects of exposure to a hard vacuum and to ultraviolet radiation which determine the suitability of a material for space application. It became apparent early in our studies, therefore, that in order to determine their value for application to manned space structures, pertinent materials must be exposed to a hard vacuum, ultraviolet radiation, and large temperature extremes for long periods of time and the degradation of properties due to this exposure measured. Accordingly, a space materials environmental test laboratory has been established.

The laboratory contains three small high-vacuum systems. The test chambers of two of the systems are 18-inch-diameter by 30-inch-high bell jars which are capable of exposing several 10-inch-long by 1-inch-wide samples of material to the simulated space environment simultaneously. The chambers have windows to allow exposure to ultraviolet sources, and liquid nitrogen cryopanels and heating coils which can provide temperature variations from -300°F to 300°F. The bell jars operate in the low 10^{-7} mm Hg pressure range. The third system contains an automatic vacuum balance which allows continuous monitoring of the weight loss of a material sample without removing it from the vacuum and thus gives an accurate indication of its rate of evaporation or decomposition in space. Our experience has shown that if a sample is exposed to a vacuum and is then removed from the chamber and weighed in air, that variations in moisture content of the sample render weight measurements meaningless. The sample chamber of this system is 6 inches in diameter and 10 inches high and is fitted with a cryopanel, a heating coil, and a window for ultraviolet exposure. The chamber operates at pressures in the low 10^{-7} mm Hg range.

Obtaining the desired ultraviolet radiation exposure has been a problem. The use of conventional equipment such as the mercury arc source and quartz windows provides UV coverage down to a wavelength of about 2000 angstrom units only. However, there are indications that some materials may be affected by radiation near the Lyman alpha line at 1216A. Consequently, a system which allows exposure down to 1000 A was developed. This was accomplished by using a hydrogen discharge tube as the source and a lithium fluoride window. However, this type of window is very thin and will withstand a pressure difference of only a few mm Hg across it. Adaptation of this window to the vacuum chamber could

not be accomplished in the usual manner, therefore, and we were forced to develop a special pressure equalizing system for this purpose.

In conjunction with this apparatus which allows exposure of materials to the more important elements of the space environment, the laboratory also contains the usual equipment such as an Instron materials tensile testing machine so that the degradation of physical properties can be determined.

The permeability of wall materials to oxygen and nitrogen is measured using a Dow cell gas-transmission tester. With this equipment, sheetmetals such as aluminum and stainless steel can be studied as well as the composite fabrics previously discussed. The Dow cells are very sensitive and gas-transmission rates of only 0.001 cubic feet of gas at standard conditions per square foot of surface per year are easy to measure.

It is of vital importance that the gases which may be given off when a material is exposed to the space environment or the gases which may collect in a closed space station environment be accurately identified. In the first place, this helps in the analysis of the mechanisms of the breakdown in space of materials such as polymers so that steps can be taken to prevent it. Secondly, it must be known whether any of the materials are releasing products which may be toxic to the crew or may have unpleasant odors. To help us identify these gases, the laboratory includes a "time-of-flight" type of mass spectrometer and a gas-liquid gas chromatograph. This equipment is used in conjunction with the vacuum chambers previously described, and a much larger chamber used for evaluating life-support systems.

In our investigation of materials in the laboratory the emphasis has been on long-term tests, and some interesting results are being obtained. For example,

samples of three different filament-elastomer composite fabrics were exposed to a pressure of 4×10^{-7} mm Hg for 140 days at room temperature and without UV exposure. Breaking tensile strength and elongation of the samples were determined before exposure and after exposures of 24, 61, and 140 days. It was indicated that a nylon-fairprene fabric which had an initial breaking strength of 335 pounds per inch lost 5 percent of its strength the first 24 days in the vacuum and then retained an approximately constant strength for the rest of the test. However, a nylon-neoprene fabric having an initial breaking tensile strength of 282 pounds per inch and a dacron-silicone sample having a strength of 115 pounds per inch were indicated to have decreased in strength about 11 percent after the 140-day exposure. The important thing here was that the decrease occurred over the whole exposure period and that there were indications that continuing small decreases might be expected upon further exposure. Additional long-term tests are being run to verify these data. No trends were evident from the breaking elongation test results.

Data obtained in the vacuum balance facility have indicated no serious weight losses for prospective flexible wall materials. A 25-square-inch sample of dacron cloth fabric coated with a polyolefin elastomer was exposed to a pressure of 5×10^{-7} mm Hg at room temperature for 14 days. The sample lost only 0.07 percent of its weight; all of this loss occurring during the first 24 hours. An 18-square-inch sample of butyl coated dacron fabric exposed to the same environment for 50 days lost 0.5 percent of its weight. This loss, however, occurred over a period of 30 days, and shows the desirability, as indicated also for the strength-loss tests, of making sure that such exposures

are continued for sizeable periods of time or until there is positive evidence that no further changes in properties are taking place.

It will be noted that no vacuum exposure work on metals has been included in the program. As has previously been indicated, this is because much is already known about the behavior of metals in the space environment, and little is known about polymers. As indicated in the literature, there appears to be no problem concerning the use of most of the structural metals in space. Aluminum, steel, and titanium, for example, must be exposed to tempertures above 1200° F before they will lose as much as 0.0004 inches of surface thickness per year. This would have no significance structurally; however, changes in the properties of surfaces could affect the absorptivity and emissivity of the material and upset the thermal balance of the space station. Also, there is little evidence that the elements of the space environment being considered here have any appreciable effect on the mechanical properties of structural metals.

It is of vital importance that a space station retain as much as possible of its initial supply of air. Provisions for extensive resupply are very costly from a launch weight standpoint. As a result, the loss of air, whether by permeability through the wall material or through joints, seams, and feed-throughs must be cut to an absolute minimum. Using the gas-transmission tester, several wall materials have been tested for leakage rates using a pressure difference of 15 psi across the sample. The results indicate that no measurable loss occurs through 1/64-inch or thicker type 2024 or 2014-T6 aluminum or type 347 stainless steel. Also, resistance-type and heli-arc welded seams have been tested in 1/64-inch and 1/32-inch aluminum and no gas transmission was apparent. Riveted joints leak badly, however, and methods of sealing these joints using Saran-type films are being investigated.

Flexible filament-elastomer fabrics, on the other hand, have objectionably high leak rates. It was indicated, for example, that even using one of the most impermeable of the elastomers, butyl, that the leak rates through a 0.1-inch thick wall would be on the order of 0.7 cubic feet of room air per square foot of surface area per year, at a pressure difference of 1 atmosphere across the wall. This amounts to about 800 pounds of air for a 150-foot-diameter torus having 10-foot cross sections. Experimental data show, however, that if a 1-mil-thick coating of a Saran-type film is put on the inside of the wall, the leakage would be reduced to about 2 pounds per year. A program is now underway to improve the bonding properties of Saran and to increase its flexibility in order to make it more compatible with heavy-fabric flexible wall construction. A second reason for using an impermeable film on the inside of the wall would be to keep the objectionable odors which some elastomers have out of the living quarters.

It appears that the problem of gases passing through the walls of a space station can be solved. However, the prevention of leakage around hatchways, airlocks, actuators, feed-throughs, etc. is another matter. This is a difficult problem requiring a large effort and is being investigated both in-house and by contracts with private companies.

One of the major problems involving materials in the space environment is that of micrometeoroid punctures. It is not possible at present to simulate the actual velocities of micrometeoroids, and therefore we cannot tell exactly what will happen to materials exposed to them. However, some preliminary results are available at lower velocities. Aluminum spheres 1/16-inch in diameter have been fired into samples of the 0.10-inch 3-ply and 0.032-inch filament-wound dacron-elastomer materials previously discussed at velocities from 6,000 to 13,000 feet per second. The resulting punctures had approximately the same

diameter as the projectile; however, the materials delaminated over 4 or 5 diameters. Firings into 2-inch cubes of these materials have resulted in penetration-to-diameter ratios of about 3.5. This indicates that for equal material weight, resistance to penetration is approximately the same as for aluminum. This means, however, that a given fabric must be 2.5 times as thick as aluminum to have the same stopping power and would therefore be hard to fold. The best solution to the micrometeoroid problem may be to use the bumper method, wherein a thin layer of material spaced on the order of an inch outboard of the structure is used to break up the object so that it does not penetrate the main structure. Such an approach is possible for either inflatable or rigid structures.

A problem area still requiring much work is that of joints and seams. Methods are required for putting together the 1800 pounds per inch materials previously discussed with a reasonable factor of safety and with a minimum of additional bulk and weight. As an initial effort in this area, approximately 20 commercial cold-setting cements have been used to join 1-inch-wide strips of dacron and nylon fabrics employing neoprene, butyl, hypalon, and silicone elastomers. Simple lap joints having 1-inch overlap were used in these tests; the joined area in each case equalled 1 square inch. The maximum joint strength so far achieved has been 400 pounds for neoprene, 275 pounds for hypalon, 275 pounds for butyl, and 45 pounds for silicone. It is realized that higher strength can be achieved by increasing the length of the lap; however, this first investigation was to determine the efficiency of existing commercial cements. Future programs include studies of variations in type and length of overlap, vulcanizing, and mechanical methods of seaming.

Our work on materials for manned orbiting space stations has only begun, and there is much more to be accomplished. We must study honeycomb structures, lubricants, rigid and flexible foams, and sealing methods. Advances must be made in filament-winding techniques — the application of glass filaments to flexible structures must be investigated. Finally, more information must be obtained on the effects of the space environment, especially micrometeoroids and particle and electromagnetic radiation, on prospective space-station materials and built-up flexible and rigid wall sections.

SOME FACTORS DETERMINING MATERIALS AND STRUCTURES PROPERTIES FOR ERECTABLE MANNED ORBITING SPACE STATION CABINS

Loads

Launch dynamic
Erection
Internal pressure
Orbital dynamic
- Stabilization impulses
- Docking Impacts
- Crew-cargo shifts

Manned Occupancy

Minimum gas leakage
Non-toxicity
No unpleasant odors
Self-sealability

Miscellaneous

High strength-to-weight ratio
Tear resistance
Easy repairability
Combustion resistance
Readily coatable

Space Environment

Temperatures: -50° F to 150° F
Hard vacuum
0-1 "g"
Electromagnetic radiation
Particle radiation
Micrometeoroids

Prelaunch and Launch Environments

High humidity: 100%
High temperature
- Ground - 140° F
- Launch - depends on shroud

Sand-fungus
Salt atmosphere
Extended storage

If Cabin is Inflatable

Repeated foldability
Inflation loads

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Figure 1. Photograph of a 24-foot-diameter flexible torus space station model inflated to a volume of 2200 cu ft. and a pressure of 7 psi.

Figure 2. Photograph of the 24-foot-diameter flexible torus space station model folded into less than 2 percent of its inflated volume.

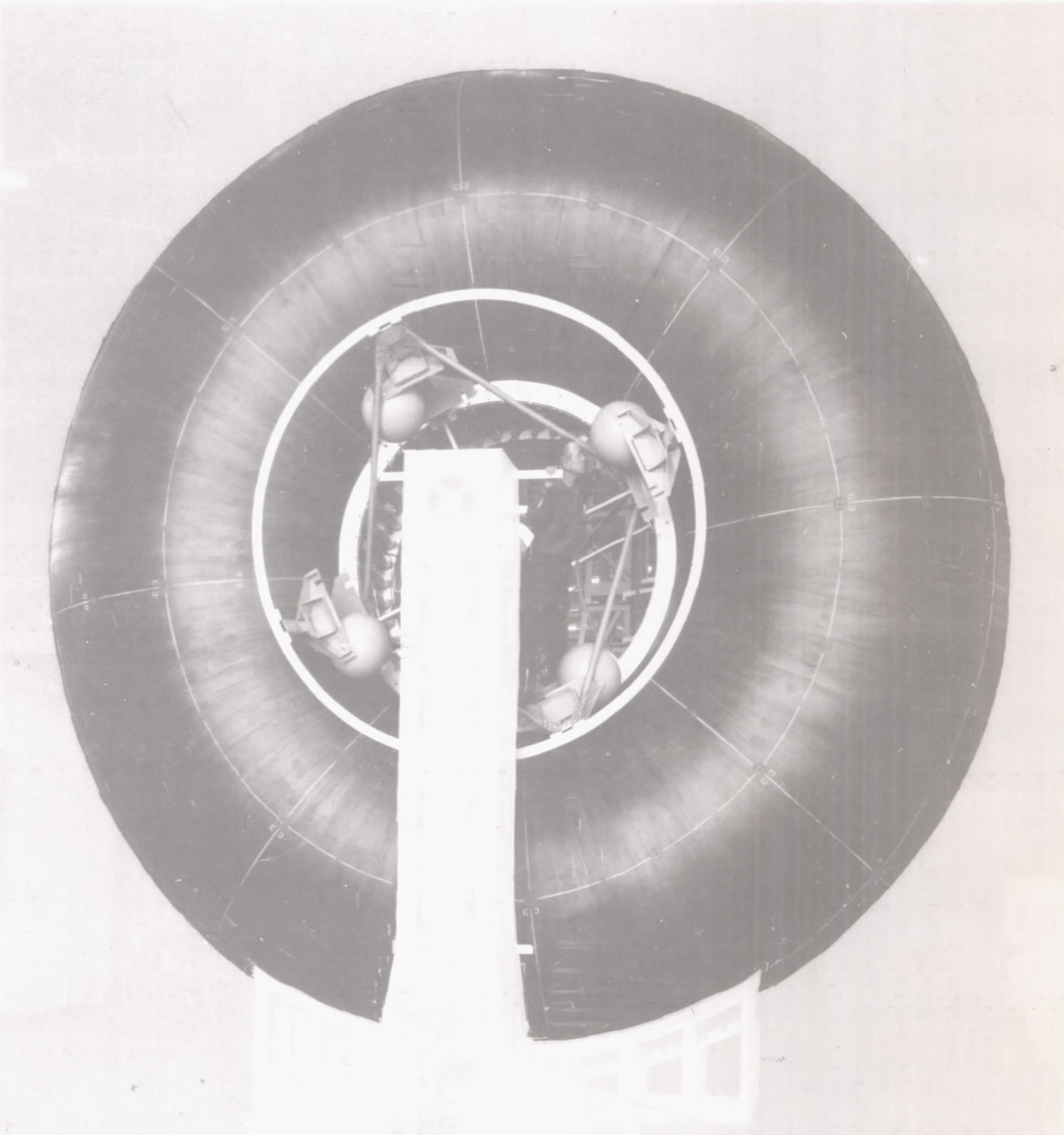
Figure 3. Schematic drawing of the filament cage and bladder construction used in building the 24-foot diameter flexible torus space station model.

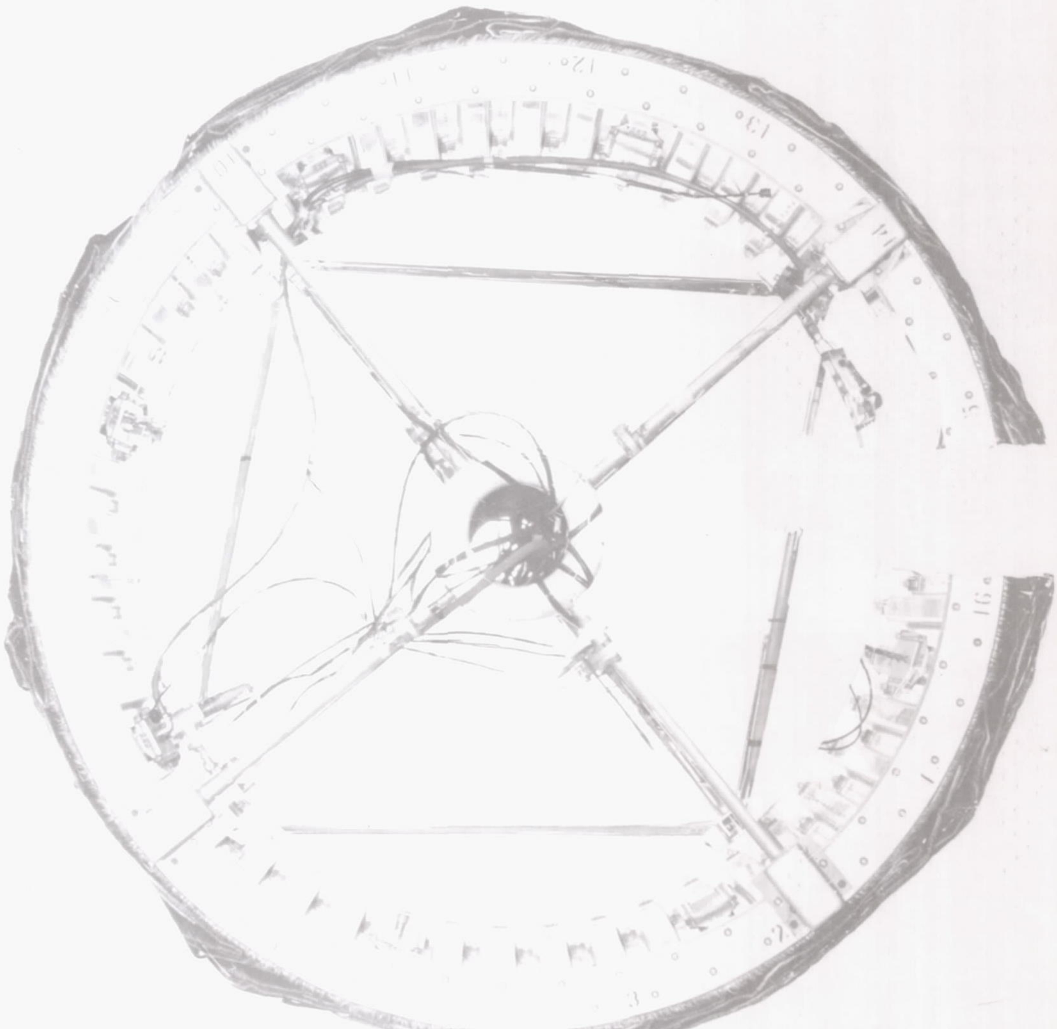
Figure 4. Schematic drawing of alternate methods of constructing flexible toroids.
Upper sketch: Isotensoid filament - wound construction
Lower sketch: 3-ply gore construction

Figure 5. Photograph of a portion of the space materials environmental test laboratory.

Figure 6. Plot showing the effects on breaking tensile strength of exposure to a hard vacuum (pressure $\approx 4 \times 10^{-7}$ mm Hg) at room temperature on various filament-elastomer combinations.
Note: the strengths of the fabrics are not comparable with one another due to differences in design.

1





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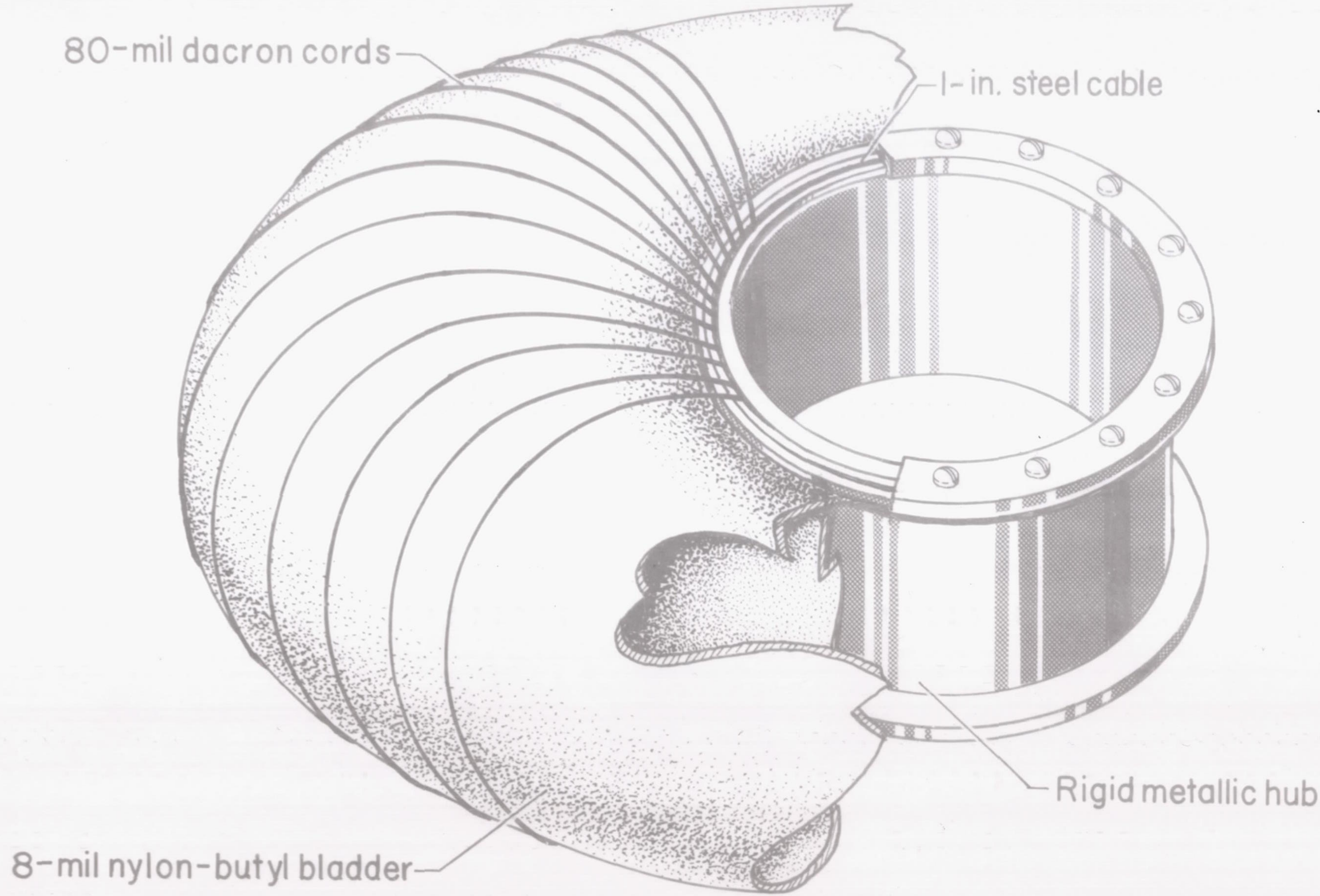
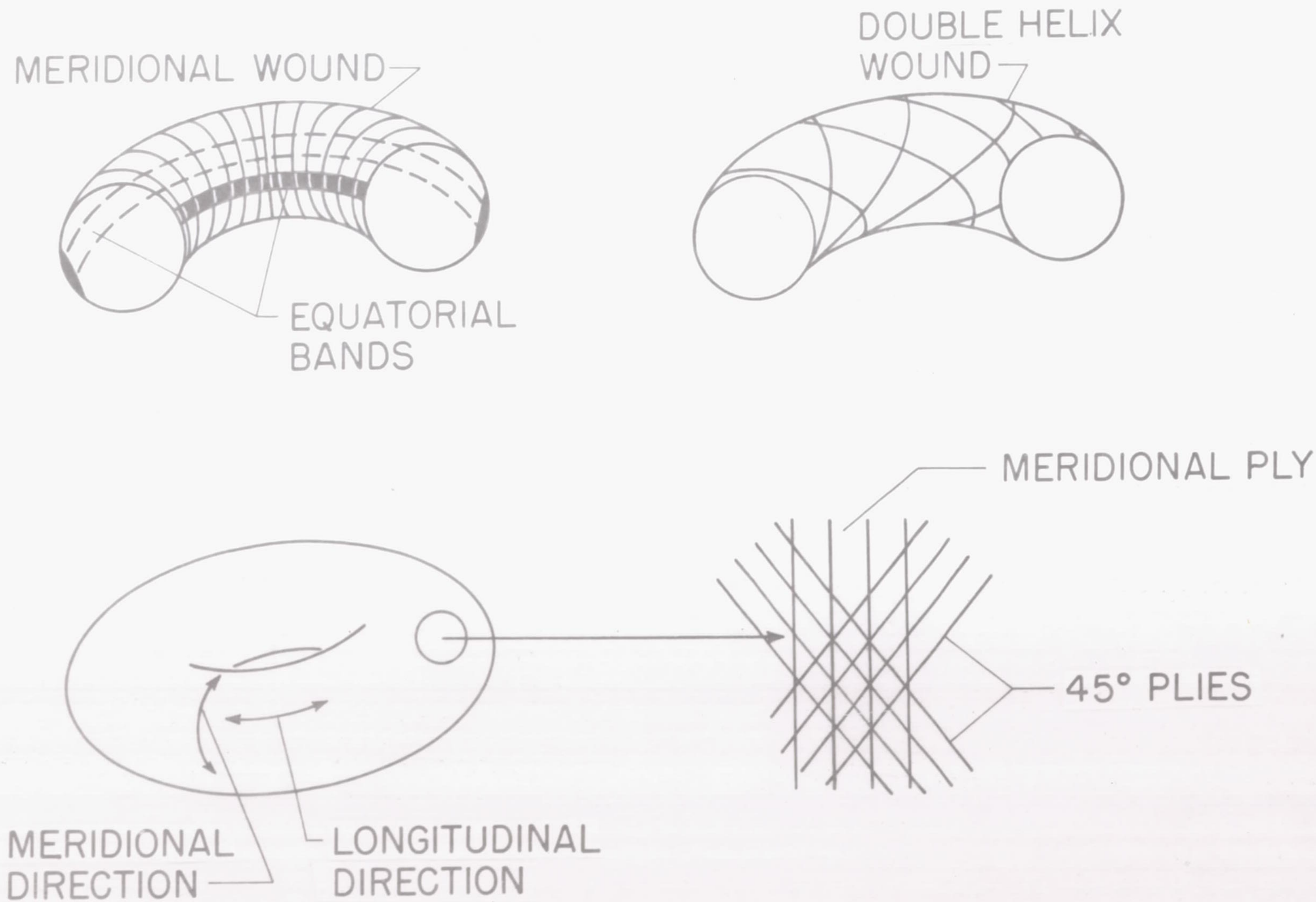
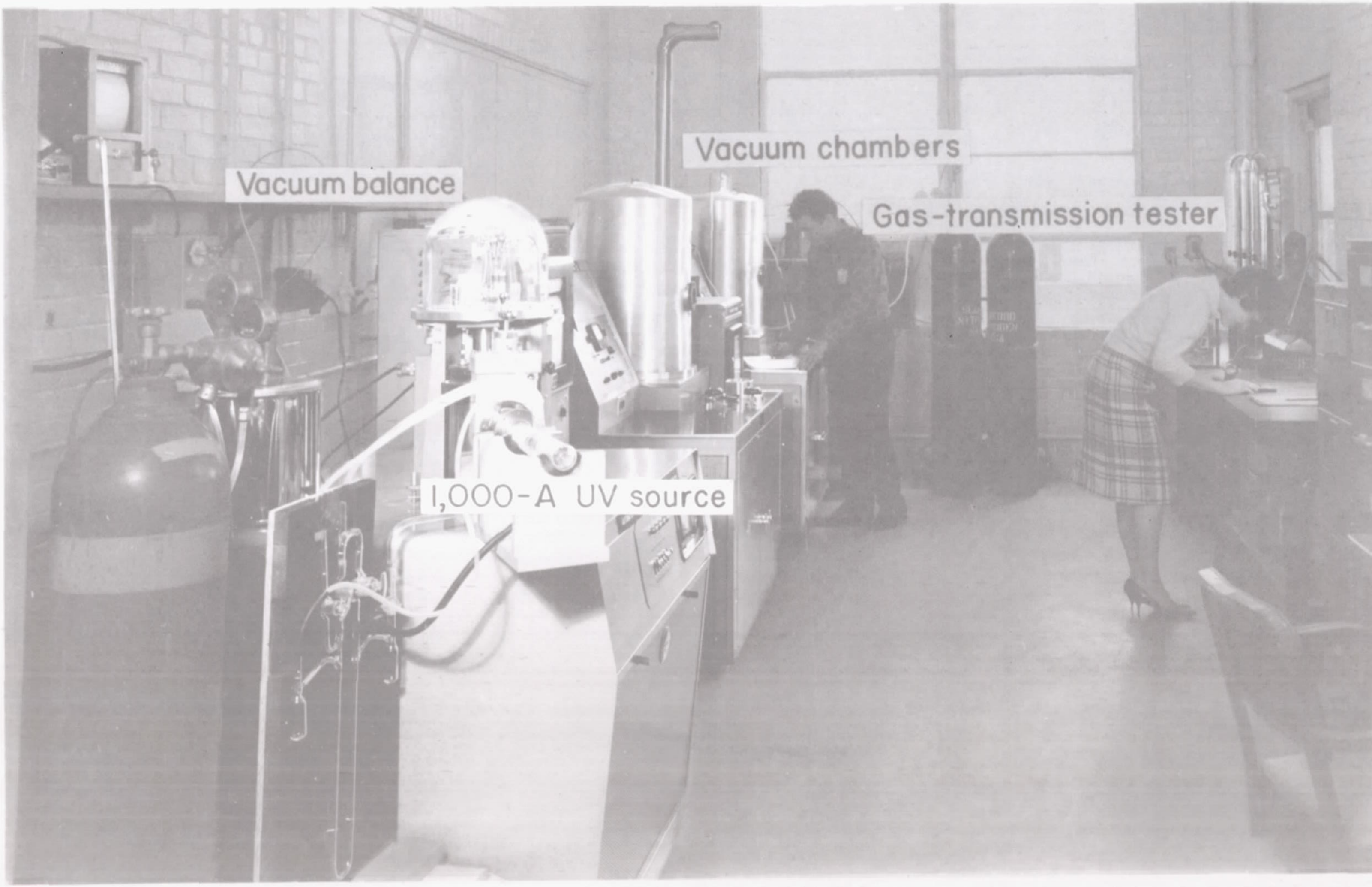

80-mil dacron cords
I-in. steel cable
Rigid metallic hub
8-mil nylon-butyl bladder

PAPER VI


MERIDIONAL WOUND
EQUATORIAL BANDS
DOUBLE HELIX WOUND
MERIDIONAL PLY
45° PLIES
MERIDIONAL DIRECTION
LONGITUDINAL DIRECTION

Paper VI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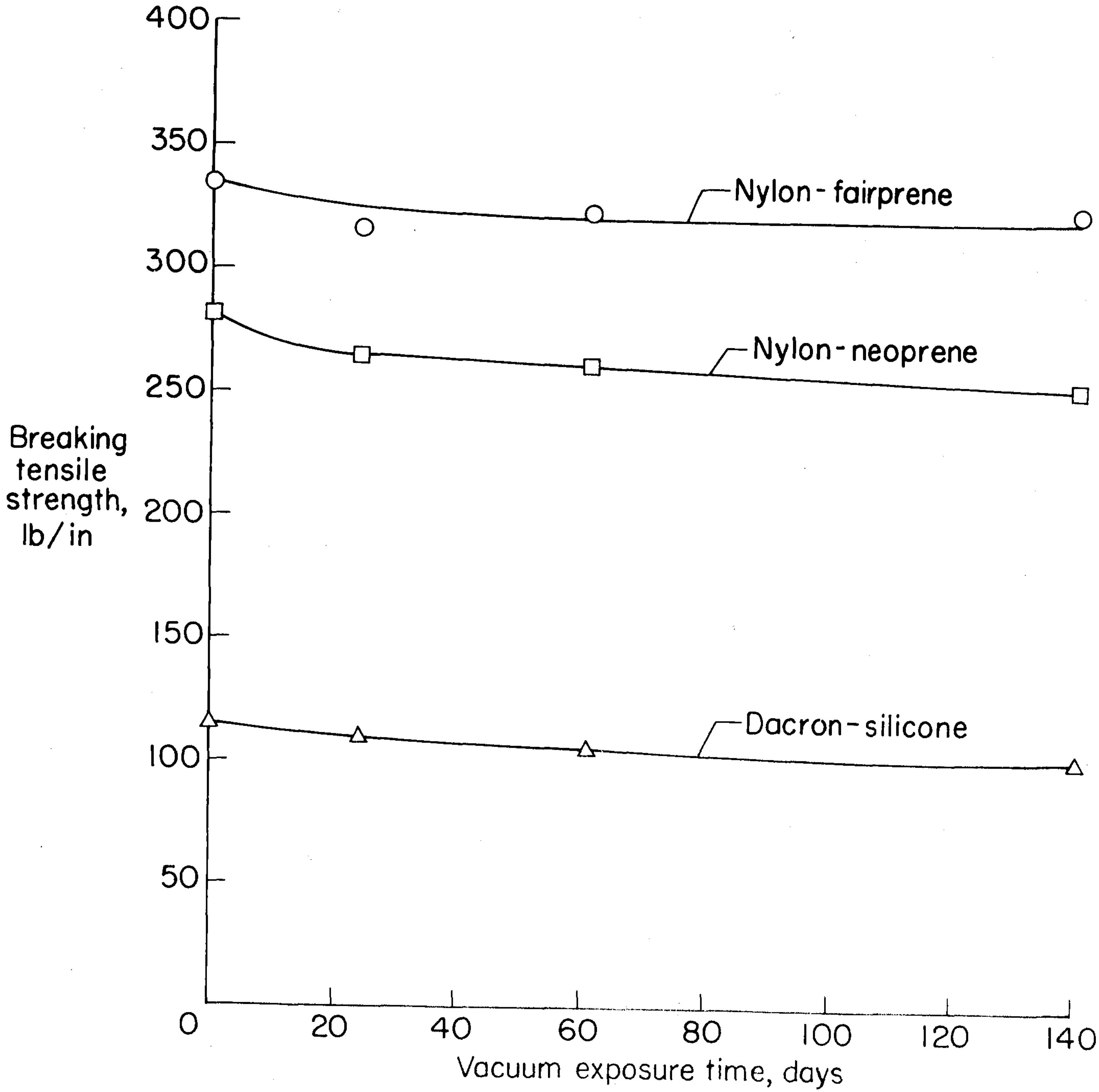
Vacuum chambers
Gas-transmission tester
1,000-A UV source


400
350
300
250
200
150
100
50
0
Breaking tensile strength, lb/in
Nylon-fairprene
Nylon-neoprene
Dacron-silicone
20
40
60
80
100
120
140
Vacuum exposure time, days

Osborne - Photo L-62-4064
Keffer - Photo L-62-4093
Look -

Robert S. Osborne, Clarence O. Keffer and George Look, co-authors of "Materials and Structures for Manned Space Stations", are all with the Space Station Office of the NASA Langley Research Center. Mr. Osborne has been in charge of the materials and structures research program for the past 3 years. Prior to that he spent 13 years with the Langley 8-ft. transonic pressure tunnel as project engineer for transonic aerodynamic stability and control research, where he made significant contributions to the design of aircraft and missiles such as the F-102, X-15, and Corvus SAM-N-8. He has a BS degree in Aeronautical Engineering from the University of Rhode Island and has done graduate work at the University of Virginia.

Clarence O. Keffer is project engineer of the twenty-four foot inflatable space station research program. This program is directed towards developing methods and techniques for folding, packaging, and deploying inflatable space stations. Before joining the Space Station Office Mr. Keffer was employed by the Space Task Group from 1958 through 1961 where he was responsible for design of recovery components for Project Mercury. Prior to this he did extensive design work on multistage solid fueled missiles for NACA.

George Look has been the project engineer of the space station materials research program for the past 2 years. Prior to that he was head chemist at Langley for 16 years, and in this capacity developed foam generators for recovery of instrument packages from space and high altitude atmospheric density payloads. He has a BS degree in Chemical Engineering from the Colorado School of Mines, has done graduate work at the University of Denver, and has worked for the Sinclair Refining Co. and the Remington Arms Co.